TECHNICAL REPORT 3031
September 2016

Characterization and Modeling of Superconducting Josephson Junction Arrays at Low Voltage and Liquid Helium Temperatures

Osama Nayfeh
SSC Pacific

Lance Lerum
Hector Romero
NREIP

Mohammed Fahem
SDSURF

SSC Pacific
San Diego, CA 92152-5001

SSC Pacific
San Diego, California 92152-5001

K. J. Rothenhaus, CAPT, USN
Commanding Officer

C. A. Keeney
Executive Director

ADMINISTRATIVE INFORMATION

The work described in this report was performed by the Advanced Concepts & Applied Research Branch (Code 71730) of the Applied Sciences Division (Code 71700), Space and Naval Warfare Systems Center Pacific (SSC Pacific), San Diego, CA.

Released by
K. Simonsen, Head
Advanced Concepts & Applied Research

Under authority of
A. D. Ramirez, Head
Advanced Systems and
Applied Sciences Division

ACKNOWLEDGMENTS

This work is funded by the Office of Naval Research (ONR) In-house Laboratory Initiative for Research managed by Dr. Dave Rees (SSC Pacific). We acknowledge the support of the Naval Research Enterprise Internship Program (NREIP) and the San Diego State University Research Foundation (SDSURF). We also acknowledge helpful discussions with Bob Fagaly (LEIDOS), Benjamin Taylor and Anna Leese de Escobar (both from SSC Pacific) and Marc Tukeman, Chuck Vinson and Mr. Mark Flemon with the procurement process. We acknowledge Deep Gupta, Saad Sarwana, and Anu Sahu and HYPRES for answering our questions regarding these Josesphson Junction arrays.

SB

EXECUTIVE SUMMARY

This technical report demonstrates the capabilities to measure Niobium-based Josephson junction arrays at liquid helium temperatures at less than 50 mV. We find current switching with voltage consistent with the transition from Cooper-pair to quasiparticle tunneling. The results agree with the industrial manufacturers specifications. We use a recently created empirical model applicable to Josephson junction devices and arrays and obtain excellent fits to the characteristics and extract the non-ideality. These capabilities and calibration results will assist in the characterization of advanced superconductor-ionic quantum memory and computation devices.

CONTENTS

Figures

1. INTRODUCTION

Josephson junctions have many applications within quantum-mechanical circuits. Their use in superconducting quantum computing is especially prevalent and relevant to this experiment. A Josephson junction is a device composed of two superconductor materials separated by a thin layer of insulation. This junction operates under the quantum tunneling effect where electrons flow through an insulating barrier. What makes the Josephson junction unique is its ability to conduct a supercurrent. While operating at cryogenic temperatures, pairs of electrons—Cooper pairs—tunnel from one side of the insulator to the other with little to no dissipation. This capability allows the devices to be operated on the millivolt scale with extremely low power consumption.

A Josephson junction has multiple parameters that characterize how it operates. It has a capacitance that is similar to that of a parallel plate capacitor. The capacitance depends on the area of the junction (A), the thickness of the insulation (d), the relative permittivity of the insulator (ε_r), and the permittivity of free space (ε_o):

$$C = \frac{\varepsilon_r \varepsilon_o A}{d}. \tag{1}$$

Josephson junctions also have a conductance G that depends on the applied voltage. Each junction has a critical current (I_C) where a voltage step occurs as well. This critical current marks the point where a junction switches from superconducting Cooper pairs to normal quasiparticle conduction. The temperature, area, and properties of the superconductors and insulators determine this critical current. The final parameter is the gauge-invariant phase difference between the two superconductors (γ). Lumping these all together, we get a comprehensive, dynamical equation for the current flowing through the junction:

$$i = I_C \sin(\gamma) + vG(v) + C\frac{dv}{dt}. \tag{2}$$

In this experiment specifically, a Nb/Al-AlOx/Nb Josephson junction array manufactured by HYPRES, Inc. is immersed in liquid helium for cryogenic measurements. The critical currents, conductance, resistance, voltage steps, and I-V curves are all observed and collected and agree with the manufacturers specifications. Accurately capturing the Josephson effect makes these measurements useful for characterization and calibration of superconducting quantum memory and computational devices.

2. EXPERIMENT

2.1 EXPERIMENTAL SET UP

As seen in Figure 1, liquid helium acquired by Defense Logistics Agency is transferred from a cryogenic dewar into a cryogenic chamber through the positive pressure applied by a compressed helium cylinder. A chip composed of an array of Josephson junctions is connected to the base of the HYPRES, Inc. probe and then lowered into the cryogenic chamber (see Figure 2). The shield room is used to protect the chip from any external electromagnetic radiation. A Keithley™ Instruments 4200-SCS Semiconductor System is connected to the probe to measure the I-V characteristics of the chip.

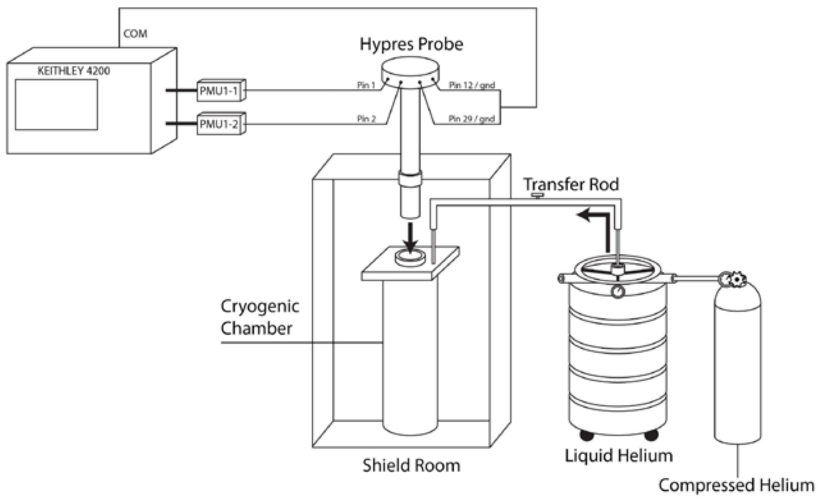

Figure 1. Schematic of experimental setup.

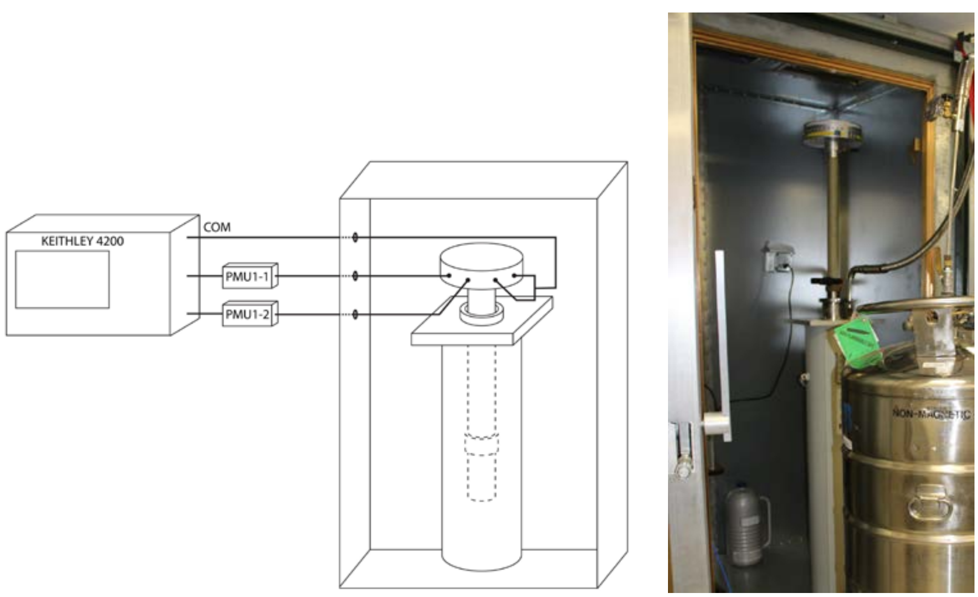

Figure 2. Schematic of electrical configuration with probe and device analyzer and the experimental arrangement in the laboratory.

The liquid helium cools the chip to below 8 °K. This experiment was performed under different temperatures to observe how this affects the superconductivity of the chip. The Keithley™ Instruments system performs a series of a current sweeps from 0 to 600 µA to obtain the I-V characteristics, as well as the resistance. Notable Josephson effects were recorded at roughly 4.2 °K, purely resistive results were recorded at higher temperatures, and a hybrid of the two effects were observed at near cryogenic temperatures.

2.2 MEASUREMENTS and DATA ANALYSIS

The first experiment was performed in the early stage of the cooling process, before the chip reached superconducting cryogenic temperatures. At this temperature, the I-V curve is linear. This linearity occurs because when the Josephson junctions are not in their superconducting state, they appear as resistors. A purely resistive system will have a linear response (see Figure 3**)**. The blue line represents the voltage as a function of current, while the orange plot represents the resistance.

Another test run of this experiment was performed closer to the desired cryogenic temperature (7 to 8 °K) as the transition temperature is ~9.2 °K for niobium. See Figure 4 for the I-V curve. We speculate that only select junctions are in their superconducting state, leading to gradually transitioning increases of current. The resistance is approximately 0.58 Ω in voltage, which corresponds to many spikes in resistance as well.

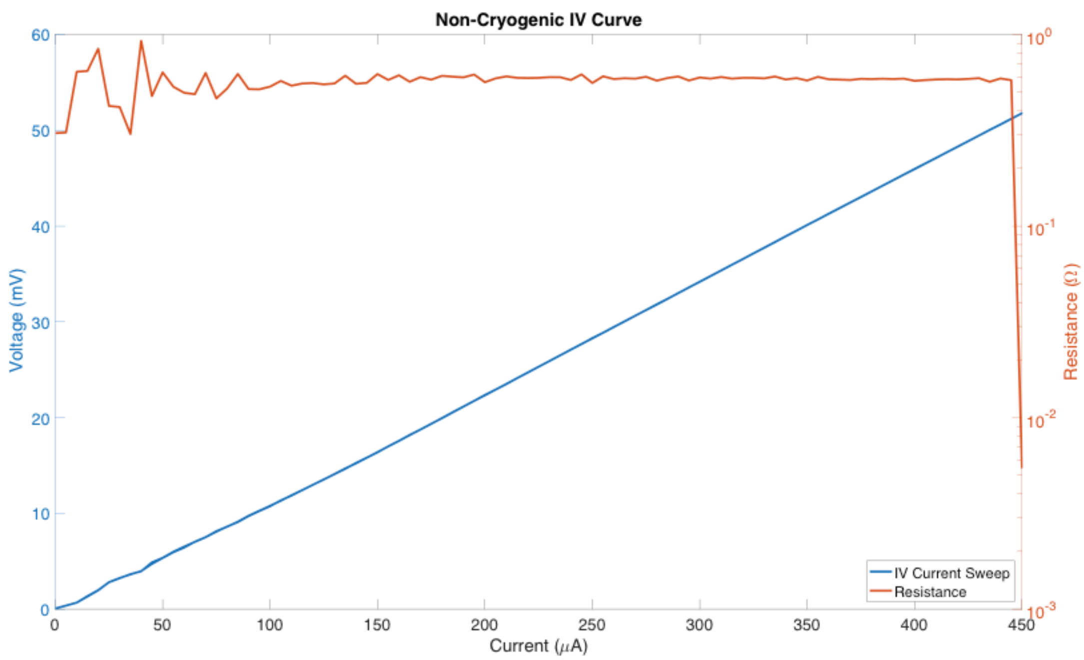

Figure 3. Measurements of the array in the resistive state with temperature greater than the critical temperature

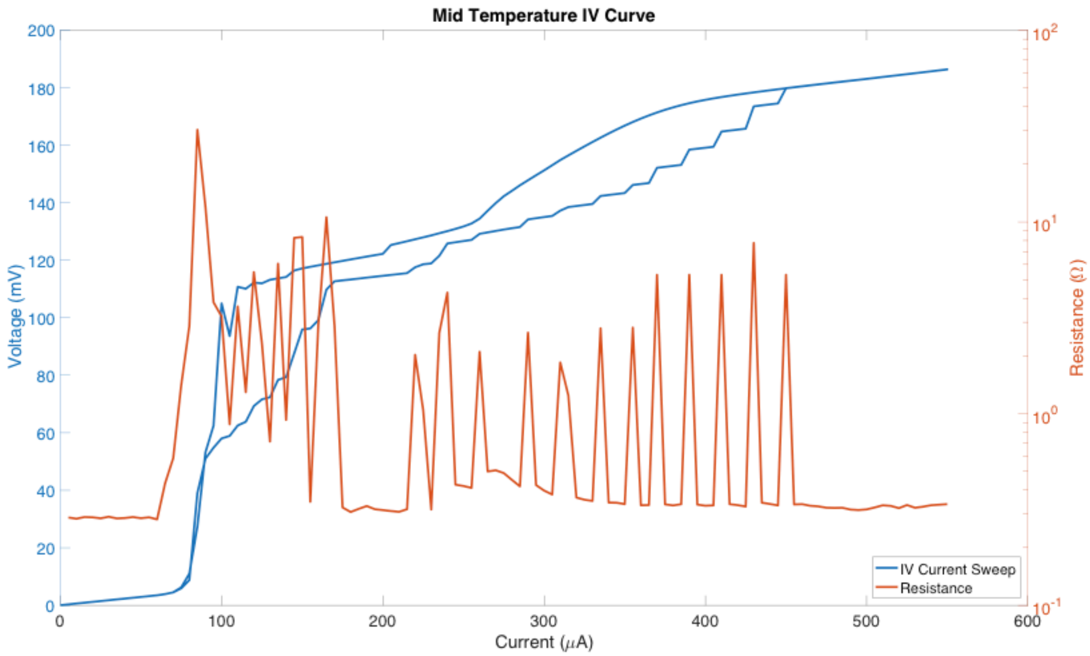

Figure 4. Measurements of the array in the cryogenic conditions near the critical temperature (i.e., 7 to 8 °K).

Once the cooling process is complete, and the chip is at liquid helium temperature (~4.2 K), the Josephson junctions' superconducting characteristics can be observed. The I-V response is no longer purely resistive. The nonlinear response can be seen in Figure 5.

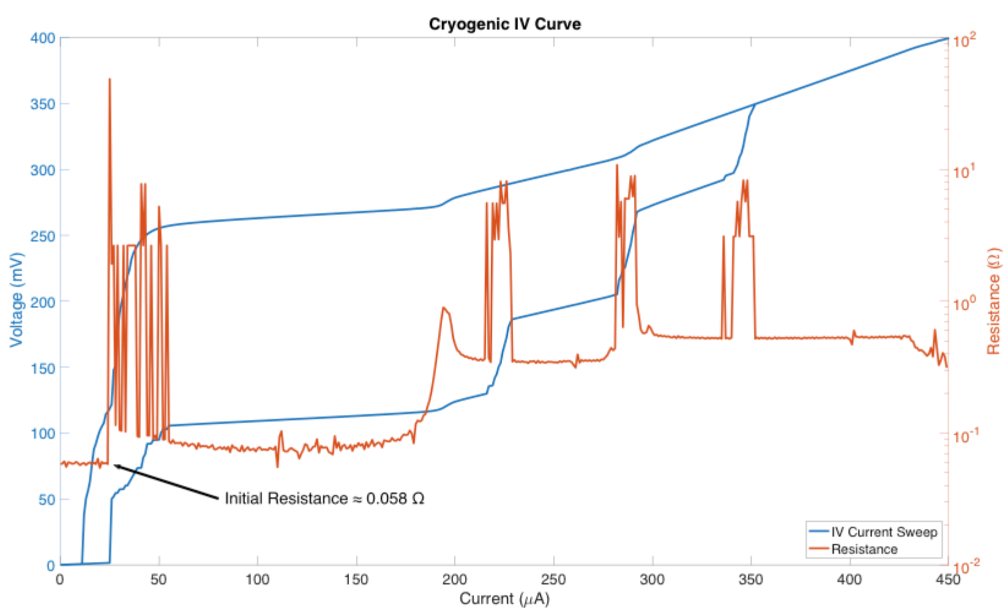

Figure 5: Measurements of the array at liquid helium ~4.2 °K with pronounced steps in current in agreement with the manufacturer's specifications.

Initially, the voltage is near zero, translating to a near zero resistance, which is important because zero resistance is needed for the preservation of quantum coherence. The location of the first jump in voltage is representative of the critical current of the first group of junctions with specific area. Once the current sweep reaches this value, a voltage drop occurs and there is a spike in resistance that correlates with the junctions subgap voltage. View Figure 6 to see this initial low-voltage spike in resistance. This group of junctions is now conducting current with a small resistance and voltage drop, which means that the quantum tunneling across these junctions now has a measurable dissipation. As the current continues to sweep, it reaches the critical currents of different Josephson junctions with larger area. Each junction's critical current leads to a voltage drop that contributes to the overall resistance. At the end of the sweep, there are no junctions superconducting, so every junction contributes a resistance. The final resistance in the normal state is approximately 0.56 Ω, which is close to the 0.58 Ω observed in the non-cryogenic case.

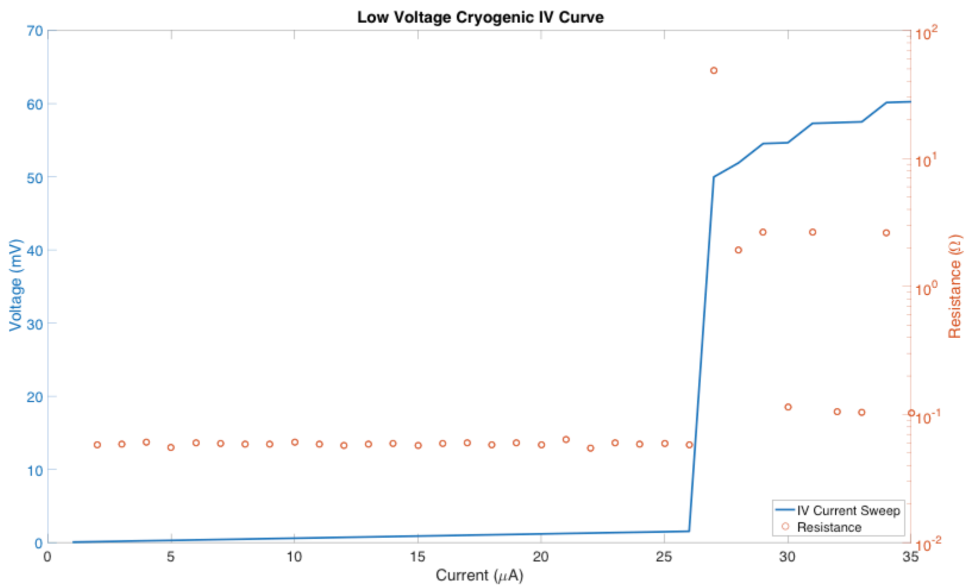

Figure 6. Close-up of the low-voltage, less than 50-mV region in the I-V characteristics for the Josephson junction array.

2.3 MODELING AND PARAMETER EXTRACTION

We recently developed an empirical formula to describe the low-voltage regime of the current switching in Josephson junctions and demonstrated the model was applicable to a wide range of junctions constructed by various superconductor electrodes and barrier materials. The expression is

$$\frac{V}{V_{sub}} = 1 - \frac{1}{1+e^{\frac{(I-I_C)}{\alpha kT}}}. \quad (3)$$

The measured steady-state I-V curve with non-idealities can be fitted by tuning the current density J_C, the fitting parameter α, the subgap voltage V_{sub} and kT, the Boltzmann constant, and the temperature product, See Figure 7 for a fitting of two different HYPRES Inc. arrays).

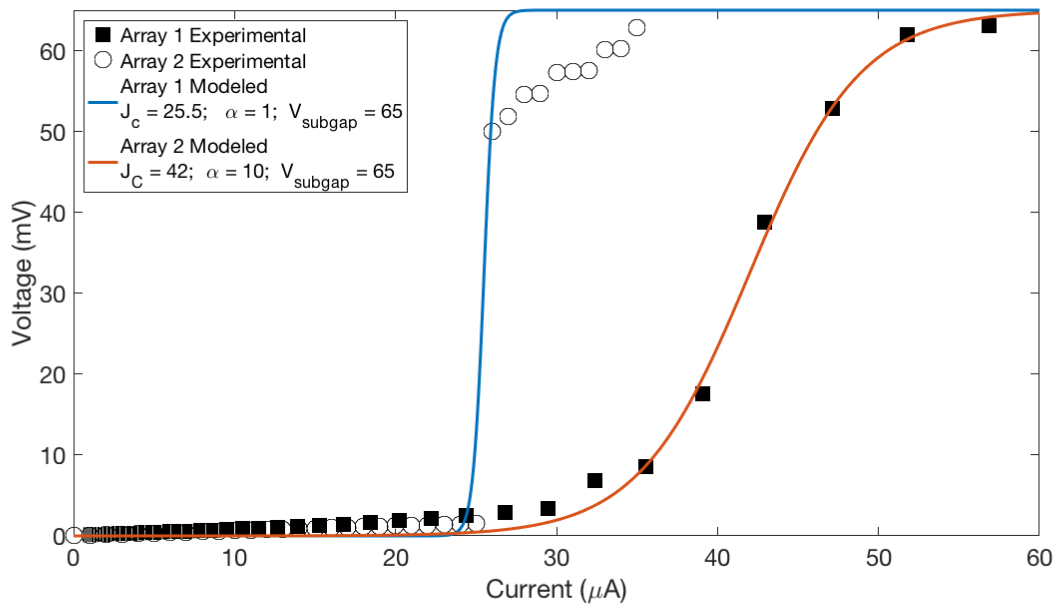

Figure 7. Excellent fitting of the Josephson junction array in the low-voltage regime less than 50 mV with our recently demonstrated empirical model.

3. SUMMARY

In summary, we demonstrated the capability to characterize and analyze Josephson junction arrays at liquid helium temperature in a shield-room and validate our recently developed empirical model for Josephson junctions. The capability will be useful for characterization and analysis of superconductor-based quantum memory and computational devices.

BIBLIOGRAPHY

H. Akaike, T. Funai, N. Naito, and A. Fujimaki. 2013. "Characterization of NbN Tunnel Junctions with Radical-nitrided AlNx Barriers," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3 (June), pp. 1101306–1101306.

S. Berggren, G. Prokopenko, P. Longhini, A. Palacios, O. A. Mukhanov, A. Leese de Escobar, B. J. Taylor, M. C. de Andrade, M. Nisenoff, R. L. Fagaly, T. Wong, E. Cho, E. Wong, and V. In. 203. "Development of 2-D Bi-SQUID Arrays iith High Linearity," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3 (June), pp. 1400208–1400208.

K. Chen, C. G. Zhuang, Q. Li, Y. Zhu, P. M. Voyles, X. Weng, J. M. Redwing, R. K. Singh, A. W. Kleinsasser, and X.X. Xi. 2010. "High-Jc MgB_2 Josephson Junctions with Operating Temperature Up to 40K," *Applied Physics Letters*, vol. 96, no. 4, 042506.

D. E. McCumber. 1968. "Effect of AC Impedance on DC Voltage-Current Characteristics of Superconductor Weak-link Junctions," *Journal of Applied Physics*, vol. 39, 3113.

E. E. Mitchell, and C. P. Foley. 2010. "YBCO Step-edge Junctions with High IcRn," *Superconductor Science and Technology*, vol. 23, no. 6, 065007.

T. Noguchi, T. Suzuki, and T. Tamura. 2011. "Subgap Tunneling Current at Low Temperatures in Nb/Al-AlN/Nb SIS Junctions," *IEEE Transactions on Applied Superconductivity*, vol. 21, no 3 (June), pp. 756–759.

T. Satoh, K. Hinode, H. Akaike, S. Nagasawa, Y. Kitagawa, and M. Hidaka. 2005., "Fabrication Process of Planarized Multi-Layer Nb Integrated Circuits," *IEEE Transactions on Applied Superconductivity*, vol. 15, no. 2 (June), pp. 78–81.

W. C. Stewart. 1968. "Current-Voltage Characteristics of Josephson Junctions," *Applied Physics Letters*, vol. 12, no. 277.

S. Tolpygo and D. Amparo. 2010. "Fabrication-process-induced Variations of Nb/Al/AlOx/Nb Josephson Junctions in Superconductor Integrated Circuits," *Superconductor Science and Technology*, vol. 23, 034024.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-01-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
September 2016	Final	

4. TITLE AND SUBTITLE

Characterization and Modeling of Superconducting Josephson Junction Arrays at Low Voltage and Liquid Helium Temperatures

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

Osama Nayfeh	Lance Lerum	Mohammed Fahem
SSC Pacific	Hector Romero	**SDSURP**
	NREIP	

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

SSC Pacific
53560 Hull Street
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER

TR 3031

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

SSC Pacific
In-house Laboratory Initiative for Research
53560 Hull Street
San Diego, CA 92152–5001

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This technical report demonstrates the capabilities to measure niobium-based Josephson junction arrays at liquid helium temperatures at less than 50 mV. We find current switching with voltage consistent with the transition from Cooper-pair to quasiparticle tunneling. The results agree with the industrial manufacturers specifications. We use a recently created empirical model applicable to Josephson junction devices and arrays and obtain excellent fits to the characteristics and extract the non-ideality. These capabilities and calibration results will assist in the characterization of advanced superconductor-ionic quantum memory and computation devices.

15. SUBJECT TERMS

superconductor ionic quantum memory; Josephson junction arrays; low voltage; liquid helium temperatures; niobium low voltage; cryogenic measurements; I-V characteristics

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Osama Nayfeh
					19B. TELEPHONE NUMBER *(Include area code)*
U	U	U	U	14	(619) 553-2770

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

INITIAL DISTRIBUTION

84300	Library	(1)
85300	Archive/Stock	(1)
71730	O. Nayfeh	(4)

Defense Technical Information Center
Fort Belvoir, VA 22060–6218 (1)

SSC Pacific
San Diego, CA 92152-5001